

# Modelling the incomplete Paschen-Back effect in the spectra of magnetic Ap stars

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## ABSTRACT

We present first results of a systematic investigation of the incomplete Paschen-Back effect in magnetic Ap stars. A short overview of the theory is followed by a demonstration of how level splittings and component strengths change with magnetic field strength for some lines of special astrophysical interest. Requirements are set out for a code which allows the calculation of full Stokes spectra in the Paschen-Back regime and the behaviour of Stokes  $I$  and  $V$  profiles of transitions in the multiplet 74 of Fe II is discussed in some detail. It is shown that the incomplete Paschen-Back effect can lead to noticeable line shifts which strongly depend on total multiplet strength, magnetic field strength and field direction. Ghost components (which violate the normal selection rule on  $J$ ) show up in strong magnetic fields but are probably unobservable. Finally it is shown that measurements of the integrated magnetic field modulus  $H_s$  are not adversely affected by the Paschen-Back effect, and that there is a potential problem in (magnetic) Doppler mapping if lines in the Paschen-Back regime are treated in the Zeeman approximation.

**Key words:** atomic processes – magnetic fields – line : profiles – stars : chemically peculiar – stars : magnetic fields

## 1 INTRODUCTION

Ever since Pieter Zeeman (1897) discovered the splitting of spectral lines in a magnetic field, astrophysicists have tried to take advantage of the diagnostic capabilities of this effect. Thanks to the Zeeman effect, G.E. Hale (1908) was able to demonstrate the presence of strong magnetic fields in sunspots and over the years countless Zeeman observations (of ever increasing precision) of lines originating in all parts of the solar atmosphere have provided deep insights into the physics of the outer layers of the sun. The discovery by Friedrich Paschen and Ernst Back (1921) that in strong fields some transitions change from the anomalous Zeeman effect to the normal Zeeman effect, has not resulted in any revision of the traditional interpretation of the observations, because even in the strongest solar magnetic fields (about 0.4 T) only very few lines are noticeably affected. Not until almost 50 years later was the question of the Paschen-Back (PB) effect in the solar spectrum first addressed by Engvold et al. (1970). Similarly, after the discovery by H.W. Babcock, starting 1947, of very strong magnetic fields in some upper-main sequence chemically peculiar stars (Ap stars), no serious thought was given to the Paschen-Back effect. Although it is clear that in a 3.4 T field like that of HD 215441

(Babcock 1960), many spectral lines would exhibit the transition from the Zeeman to the PB regime (which we shall call the incomplete or partial PB effect), the first papers on the Paschen-Back effect in a stellar context appeared only much later (Kemic 1975; Stift 1977).

Recently, interest in the Paschen-Back effect has revived, mainly in the solar context and for molecular lines. As to atomic transitions, let us note that the He I 10830 Å triplet has received special attention (Socas Navarro et al. 2004), as has for example the Mn I 15262.7 Å line (Asensio Ramos et al. 2007). In the stellar context, the work of Mathys (1990) constitutes a particularly detailed modelling attempt and discussion of the incomplete PB effect in the Fe II lines at  $\lambda$  6147.7 and  $\lambda$  6149.2. The PB effect on hyperfine structure and its observational consequences have been investigated by Landolfi et al. (2001). It should be kept in mind that these results have generally been obtained in the Milne-Eddington approximation, and that heavy blending as often found in Ap stars could not be taken into account.

Our interest in the Paschen-Back effect has been stimulated by the difficulties we encountered when trying to match high resolution spectral observations of strongly magnetic Ap stars with synthetic spectra (see Fig. 1). The Zeeman doublet of Fe II at 6149 Å in particular not only dis-

plays non-symmetric relative intensities of the components – already noted by Mathys (1990) – but it also proves impossible to model the velocity shift (relative to the reference RV determined from magnetic null lines of iron) within the Zeeman regime. From Fig. 1 it emerges that even at the very moderate field strength of 0.36 T this shift is already observable.

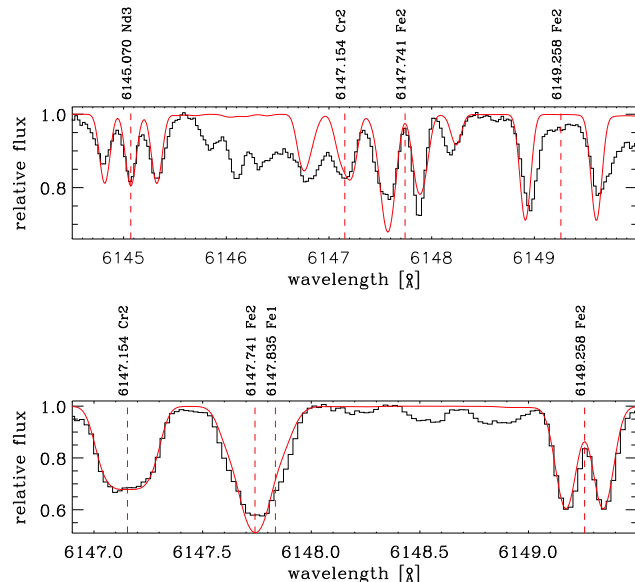
Assuming that the Paschen-Back effect is responsible for both asymmetries and shifts, the question naturally arises whether the measurement of the magnetic field modulus  $H_s$  (the absolute field strength integrated over the visible hemisphere), which is based on the interpretation of the observed splitting of the  $\lambda 6149$  line in terms of simple Zeeman splitting, may be systematically affected by the PB effect. This has not been studied so far, and we are also not aware of any discussion in the literature of the observed shift of the  $\lambda 6149$  line.

In the past, neither computers nor codes were powerful enough to embark on any ambitious program of modelling stellar Stokes profiles in the incomplete PB regime. Now that multi-processor and/or multi-core architectures have become affordable, COSSAM (Stift 2000) – a state-of-the-art object-oriented and fully parallel Stokes code – has been modified in such a way as to allow the calculation for realistic stellar atmospheres of a multiplet in the incomplete PB regime, with full blending from the remaining spectral lines which are assumed to display classical anomalous Zeeman patterns. These tools make it possible to systematically explore how the observed Stokes profiles are affected by the partial PB effect, to have a close look at the diagnostic content of Paschen-Back lines, and to model in detail selected spectral intervals in Ap stars with very strong fields. First important results are presented in this paper.

## 2 THE INCOMPLETE PASCHEN-BACK EFFECT

Named after the two German physicists Friedrich Paschen and Ernst Back, this effect generalises to magnetic fields of arbitrary strengths the better known Zeeman effect. The effect was discovered in the laboratory in various multiplets (Paschen & Back 1921), including the  $4s4d^3D \rightarrow 4s4p^3P$  multiplet of Zn I that was later studied in major detail by van Geel (1928). The Paschen-Back effect has been successfully interpreted within the framework of quantum mechanics, and nowadays this interpretation can be found in classical textbooks of atomic and/or molecular spectroscopy (see e.g. Condon & Shortley 1935).

In order to recall the basic physical facts, let us consider a term of an atom, characterised by the quantum numbers  $L$  and  $S$ . The term is composed of  $2S + 1$  (or  $2L + 1$  if  $L < S$ )  $J$ -levels whose energy separation is due to the spin-orbit interaction. When a weak magnetic field is present, each  $J$ -level splits into  $2J + 1$  magnetic sublevels that can be identified by the further quantum number  $M$ . In as far as the magnetic splitting is much lower than the fine-structure separation between different  $J$ -levels, such splitting turns out to be proportional to the magnetic field, and the atom is said to be in the Zeeman effect regime. However, when the magnetic field starts to be comparable, or even larger than the fine-structure separation between  $J$ -levels, the linearity

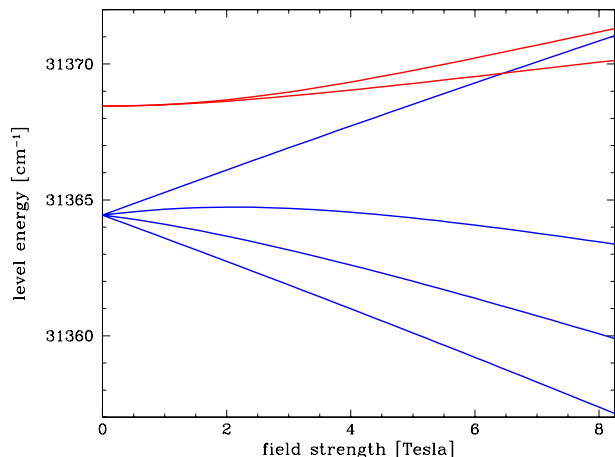


**Figure 1.** RV-corrected Stokes  $I$  spectra in the vicinity of the Fe II lines at 6147 and 6149 Å of the stars HD 66318 (top) and HD 188041 (bottom). The magnetic field modulus is 1.5 T for the former star, 0.36 T for the latter. The dashed red lines give the zero field positions of the lines of Cr, Fe and Nd. The full red lines are plotted for the only purpose of illustrating the line shift in  $\lambda 6149$ ; they result from a straightforward spectral synthesis, assuming normal Zeeman splitting. The RV has been determined from the magnetic null lines ( $g_{\text{eff}} = 0.0$ ) of Fe I at  $\lambda 5434.52$  and  $\lambda 5576.09$ .

property is lost and the atom enters the regime of the (incomplete) Paschen-Back effect. Here the situation is more complicated because the quantum number  $J$  is no longer a good quantum number and the atomic levels can thus be characterised only by the magnetic quantum number  $M$ , not by  $J$ .

The energy values of the levels (the eigenvalues) and the corresponding eigenvectors can be obtained by diagonalisation of a set of matrices. The details of this procedure and the relevant equations are described in full detail in Sect. 3.4 of the monograph by Landi Degl’Innocenti & Landolfi (2004). In the same book one can also find the expressions for the splitting and the strengths of the various components ( $\sigma_{\text{red}}$ ,  $\pi$ , and  $\sigma_{\text{blue}}$ ) that arise in the transition between a lower and an upper term, both in the Paschen-Back regime. The remarkable fact is the appearance of some extra-components that can be referred to as “satellite” or “ghost” components. These components are strictly forbidden in the absence of a magnetic field, and have negligible strengths in the Zeeman effect regime, because of the selection rule  $\Delta J = \pm 1, 0, 0 \not\rightarrow 0$ . Referring for instance to the above-mentioned multiplet of Zn I, the multiplet contains 6 lines in the Zeeman regime ( $J_{\text{low}} = 0 \rightarrow J_{\text{up}} = 1, 1 \rightarrow 1, 1 \rightarrow 2, 2 \rightarrow 1, 2 \rightarrow 2, 2 \rightarrow 3$ ), but the number of lines increases to 9 in the Paschen-Back regime. At the same time, the number of magnetic components increases from 54 (18  $\sigma_{\text{red}}$ , 18  $\pi$ , and 18  $\sigma_{\text{blue}}$ ) in the Zeeman regime to 71 (23  $\sigma_{\text{red}}$ , 25  $\pi$ , and 23  $\sigma_{\text{blue}}$ ) in the Paschen-Back regime.

The fact that strong magnetic fields are capable of



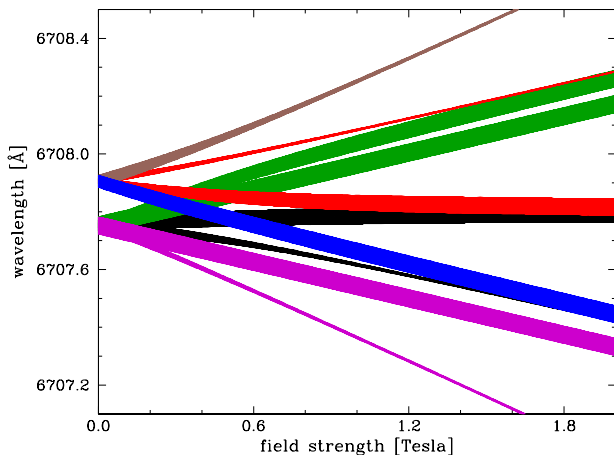
**Figure 2.** Magnetic splittings of the lowermost 2 levels of the  $^4D$  term of Fe II multiplet 74 as a function of field strength.

bringing out lines which violate the ordinary selection rule on  $J$  was indeed the most important hint which led to the original discovery of the Paschen-Back effect. Examples of this behaviour and further properties concerning the strengths and the splittings of the components are described in the following sections of the present paper.

### 3 ENERGY LEVEL SPLITTINGS AND RELATIVE COMPONENT INTENSITIES

The theory of the incomplete Paschen-Back effect reveals that both the splittings of the energy levels in a multiplet and the relative intensities of the subcomponents can change in a non-linear way with the magnetic field strength. Whether or not this happens at field strengths typical for Ap stars (0.1 - 3.5 T) depends on the detailed fine structure splittings of the terms involved. It is useful to recall that a field strength of 1 T corresponds to a splitting of  $0.47 g M \text{ cm}^{-1}$ , where  $g$  denotes the Landé-factor and  $M$  the magnetic quantum number. Taking as an example the  $^4D$  term of Fe II multiplet 74 (which gives rise to the well-known lines at  $\lambda 6147$  and at  $\lambda 6149$ ), the magnetic splitting of the  $J = 3/2$  level can exceed the distance to the neighbouring  $J = 1/2$  level for fields of about 4.7 T. From detailed calculations it emerges that deviations from simple Zeeman splitting occur much earlier: very close scrutiny of the respective positions of the blue and red doublet components relative to the zero field wavelength reveals a difference of about 20 mÅ (the total splitting is 330 mÅ) at only 0.7 T (see Fig. 2).

The famous Li I  $\lambda 6707$  doublet is another interesting case that has attracted some attention over the past decades (let us mention Engvold et al. (1970), Mathys (1991), and Leone (2007)). Its fine structure splitting amounts to a mere  $0.34 \text{ cm}^{-1}$  and can be exceeded by magnetic splitting already at field strengths of 0.5 T. Again, detailed calculations show that deviations from simple Zeeman splitting become clearly visible somewhat earlier than 0.2 T (Fig. 3). The surprise however comes when one looks at the relative intensities of the 4 sub-components of  $\lambda 6707.912$ : already at a bare 0.05 T, the two  $\pi$ -components differ by 20 %, and the re-



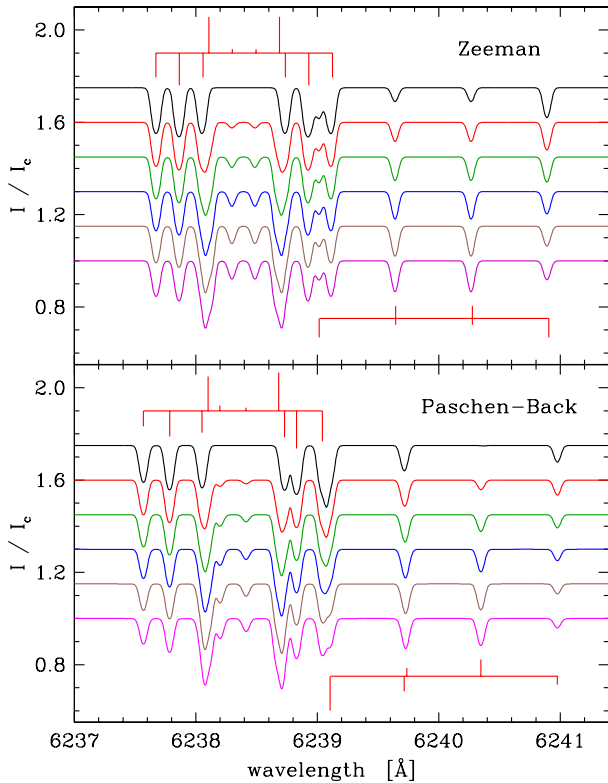
**Figure 3.** Wavelength splittings and relative intensities of the subcomponents of the Li I  $\lambda 6707$  doublet as a function of magnetic field strength. For clarity, the respective  $\pi$  components are plotted in black and red, the  $\sigma_{\text{blue}}$  components in magenta and blue, and the  $\sigma_{\text{red}}$  components in green and brown.

spective  $\sigma$ -components by 10%! At the still very moderate field strength of 0.1 T, these values rise to 44 % and 20 %.

How many spectral lines will then be subject to the partial Paschen-Back effect in strongly magnetic Ap stars? This is no easy question to answer but a quick search in the NIST energy level tables already provides a substantial number of candidate terms for some elements: there are for example 18 terms of Cr I with energies up to  $52000 \text{ cm}^{-1}$  where at least 1 pair of neighbouring levels are separated by less than  $5 \text{ cm}^{-1}$ . It is mostly possible to identify the lines originating from these terms in the Kurucz (1993b) line-list and the surprising result is that a staggering 18 % or 2320 lines out of some 13000 may be affected by the partial Paschen-Back effect in Ap stars with strong magnetic fields. The lowest  $^5G$  term alone where the splittings between adjacent levels vary between  $0.25 \text{ cm}^{-1}$  and  $2.77 \text{ cm}^{-1}$  gives rise to 846 lines. Are there important lines among these? Have they been used for example for magnetic Doppler imaging or for abundance analyses? For the moment we do not know; we need not be overly alarmist but the possibility cannot be ruled out and it is not quite clear what the consequences would be.

### 4 PARTIAL PASCHEN-BACK EFFECT AND STOKES PROFILE MODELLING

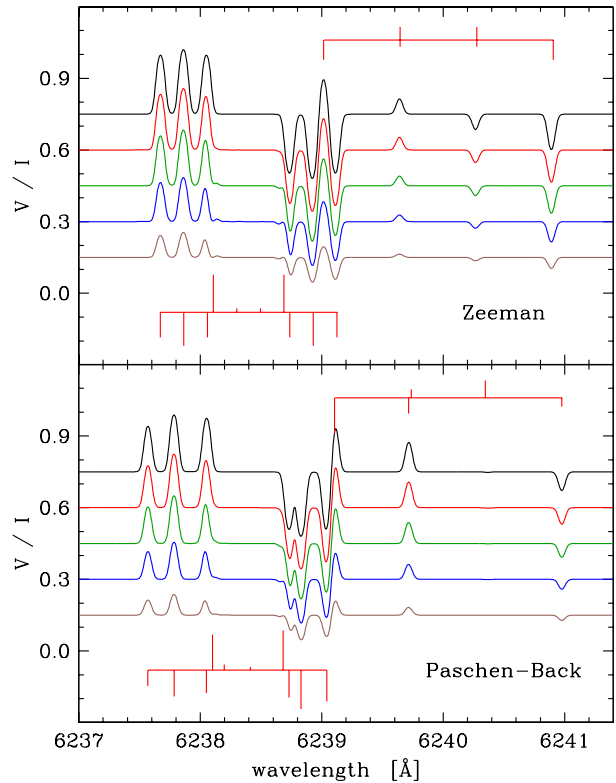
The tool for our modelling investigations into the partial Paschen-Back effect is CossamPaschen, a new version of the COSSAM code developed by Stift (2000). COSSAM is a state-of-the-art line synthesis code (Wade et al. 2001) that allows the calculation of full Stokes spectra either in the solar case (one specific point on the solar surface) or the stellar case (spatial integration of the profile over the visible hemisphere of the star). The code is characterised by LTE in a plane-parallel atmosphere, continuous opacities taken from Atlas9 or Atlas12 (Kurucz 1993a, 2005), full component by component opacity sampling (CoCoS), and by the choice between the Zeeman Feautrier (Alecian & Stift 2004) and the DELO (Rees et al. 1989) formal polarised solvers.



**Figure 4.** Stokes  $I$  profiles for the Fe II lines at  $\lambda 6238.392$  and  $\lambda 6239.953$  belonging to multiplet 74, both in the Zeeman and in the partial Paschen-Back regime. Calculations have been carried out for a 12000 K,  $\log g = 4.0$  Kurucz (1993a) atmosphere, the magnetic field strength is 2 T, and the respective angles between field direction and line-of-sight are 0, 30, 45, 60, 75, and 90° (from top to bottom). The corresponding Zeeman and Paschen-Back patterns of the two lines are shown in the conventional form of vertical bars, with the  $\pi$ -components above and the  $\sigma$ -components below the axis.

In the Zeeman regime where subcomponent splittings can be assumed to scale linearly with magnetic field strength, one just has to store the respective anomalous Zeeman patterns for each line in the atomic data list. Splittings for any point on the stellar surface are determined by simple multiplication with a field-dependent factor. Relative intensities are independent of field strength which implies that both in the solar and in the stellar case, storage requirements are restricted to just one set of Zeeman splittings and relative intensities of the Zeeman subcomponents.

Not so in the partial Paschen-Back regime. We have seen that splittings and relative subcomponent intensities go non-linearly with field strength. For each point on the stellar surface (and there have to be several hundreds to a few thousands of points depending on field geometry and on rotation) one has to determine the exact splittings and relative intensities for the given local field strength by the usual diagonalisation of the total Hamiltonian as outlined before. One then has the choice of synthesising separately all the local profiles before combining them to an integrated profile or to store the local Paschen-Back patterns in some



**Figure 5.** The same as in Fig. 4, but for Stokes  $V$ . The case of 90° is omitted.

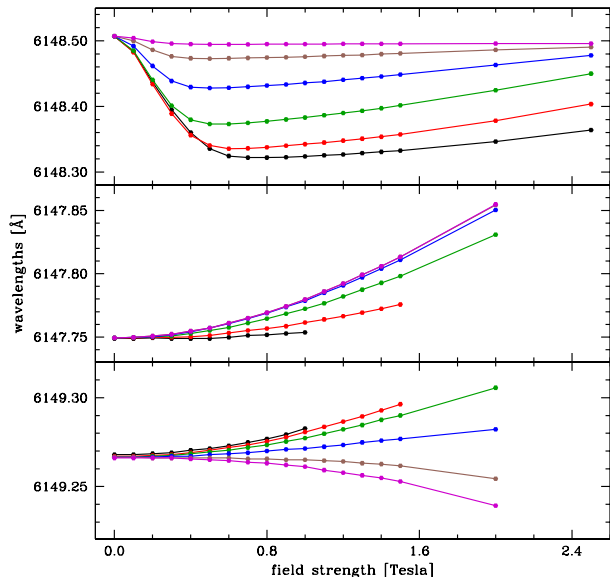
appropriate structure and proceed first with spatial integration at each wavelength point. Memory requirements will be substantial, especially in the latter case.

Since few if any of the lines of astrophysical interest which exhibit the transitions to the Paschen-Back effect are entirely unblended, it is important to account for blending and to include the full list of lines appropriate to the stellar atmosphere. The final version of CossamPaschen thus allows the modelling of the full Stokes profiles of the transitions in one multiplet under the partial Paschen-Back regime, blended with all other transitions found in the interval in question and treated in the Zeeman approximation.

## 5 STOKES PROFILES: ZEEMAN VS. PASCHEN-BACK

Differences between Stokes profiles calculated in the simple Zeeman regime and profiles calculated in the partial Paschen-Back regime can range from subtle to spectacular. Zeeman components are shifted, get stronger or fade, symmetries are destroyed, blends start to look quite different. The lines  $\lambda 6238.39$  and  $\lambda 6239.95$  of the Fe II multiplet 74 beautifully illustrate these changes for a field strength of 2 T. The former line, a  $^4D_{3/2} - ^4P_{3/2}$  transition, and the latter, a  $^4D_{1/2} - ^4P_{3/2}$  transition, have together 6  $\pi$  components and 5  $\sigma_{\text{blue}}$  and  $\sigma_{\text{red}}$  components.

The most spectacular changes occur for a longitudinal field. The component near 6240.4 Å disappears while



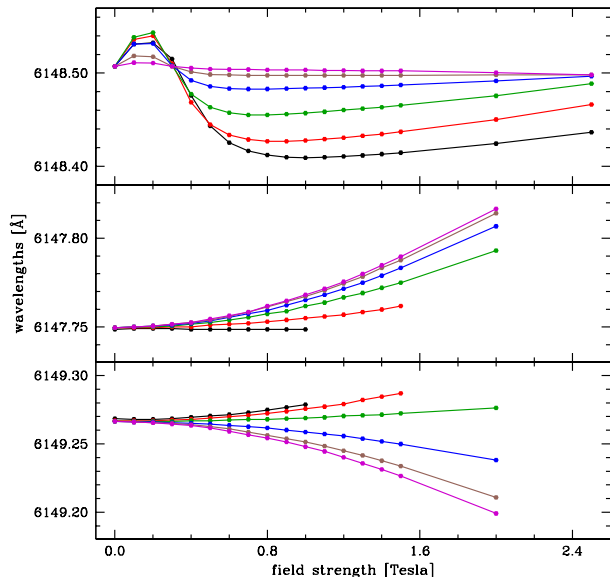
**Figure 6.** Wavelengths of the respective centres-of-gravity in Stokes *I* of the synthesised Fe II lines at  $\lambda$  6149 (bottom) and at  $\lambda$  6147 (middle) as a function of magnetic field strength and of abundance. The curves (black, red, green, blue, brown, magenta) correspond to decreasing abundances in steps of 0.5 dex. Wavelengths of the centre-of-gravity of the 2 lines taken together are shown in the top panel. The field is taken to be longitudinal.

at the same time the component near 6239.6 Å increases in strength (see Fig. 4). The outer  $\sigma_{\text{blue}}$  component becomes stronger too, and the blend with the  $\sigma_{\text{red}}$  components of  $\lambda$  6238.39 completely changes shape. In Stokes *V* we also note the conspicuous weakening of the  $\sigma_{\text{red}}$  components of  $\lambda$  6239.95; a positive *V* signal emerges to the right of the blend (Fig. 5). Changes remain clearly visible in a transversal field, although they are no longer as important as in the longitudinal case. Note that in the Paschen-Back regime, some components hardly change intensity with angle.

The reason for the disappearance of the component near 6240.25 Å is easily explained:  $\pi$ - and  $\sigma_{\text{red}}$ -components are almost exactly at the same position, but the intensity of the  $\sigma_{\text{red}}$ -component is now by more than a factor of 30 lower than in the Zeeman regime. The intensity of the red  $\pi$ -component grows by about a factor of 1.6. The inner  $\sigma_{\text{blue}}$ -component of  $\lambda$  6239.95 displays an intensity increase by a factor of 2.5, the outer one by a factor of 1.8, whereas the blue  $\pi$ -component weakens.

## 6 SELECTED RESULTS

There has not been in the past any systematic investigation of the incomplete Paschen-Back effect in the Stokes spectra of strongly magnetic Ap stars. Only the pioneering work by Mathys (1990) has provided valuable insight and raised interesting questions. We have tried to extend these results and we want to illustrate here some salient points of our findings, especially concerning the Fe II doublet at 6149 Å and its use in the determination of the magnetic field modulus.



**Figure 7.** The same as in Fig. 6 but for a transverse field.

### 6.1 Line shifts

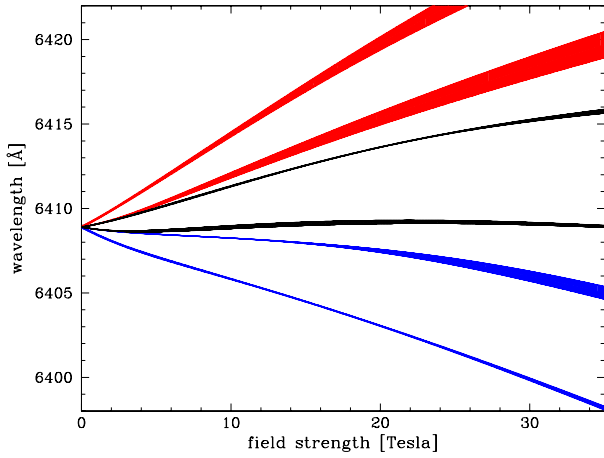
The findings presented in Sec. 3 warrant detailed modelling of selected lines in order to determine the wavelength shifts that could show up in the incomplete Paschen-Back regime. Indeed, the notable deviations from linear Zeeman splitting in a number of well-studied lines, together with the rapidly changing relative intensities of the subcomponents should necessarily not only lead to asymmetries in the line profiles but also to line shifts of various amounts and different signs. Such shifts are found e.g. for the Fe II line at 6149 Å in HD 126515 (see also Figs. 7 and 8 of Mathys (1990) and cannot be modelled in a pure Zeeman regime.

For instructive purposes we have therefore chosen the Fe II  $\lambda$  6147 and  $\lambda$  6149 lines and calculated high resolution synthetic profiles for various field strengths up to 3 T and for a number of abundances in steps of 0.5 dex. Considering the longitudinal and the transverse case, we obtained a grid of 228 models which cover enough of parameter space to allow a meaningful discussion.

Based on our polarised spectral line synthesis, we note for a longitudinal field of 2 T and in the weak-line limit a marginal blue-shift ( $-0.027$  Å) of the centre-of-gravity (COG) of the  $\lambda$  6149 doublet and a clear red-shift ( $+0.11$  Å) of  $\lambda$  6147 (see Fig. 6). The COG of the 2 lines combined remains almost unaffected ( $-0.01$  Å). The COGs are determined from the Stokes *I* profiles. Interestingly, for very strong lines and 1 T (larger field strengths lead to blending), the situation is partially inverted with the  $\lambda$  6149 doublet slightly ( $+0.015$  Å) red-shifted and  $\lambda$  6147 essentially unchanged. The COG of the 2 combined lines however is now blue-shifted by a remarkable  $-0.18$  Å).

In the case of a transverse 2 T field, the weak-line limit leads to a noticeable ( $-0.07$  Å) blue-shift of  $\lambda$  6149 and a red-shift of exactly the same size ( $+0.07$  Å) of  $\lambda$  6147 (see Fig. 7). Again, the COG of the 2 lines combined remains almost unaffected ( $-0.01$  Å). Very strong lines and a 1 T field yield a marginally ( $+0.01$  Å) red-shifted  $\lambda$  6149 doublet and





**Figure 8.** Splittings and relative intensities of the subcomponents of the “ghost line” at  $\lambda 6408.9$  (belonging to multiplet 74 of Fe II). The respective  $\sigma_{\text{blue}}$ ,  $\pi$  and  $\sigma_{\text{red}}$  components are plotted in different colours.

$\lambda 6147$  unchanged. The blue-shift of the COG of the 2 lines combined is reduced to  $-0.10$  Å) but surprisingly we now also encounter a red-shifts of up to  $0.025$  Å for fields of less than  $0.3$  T.

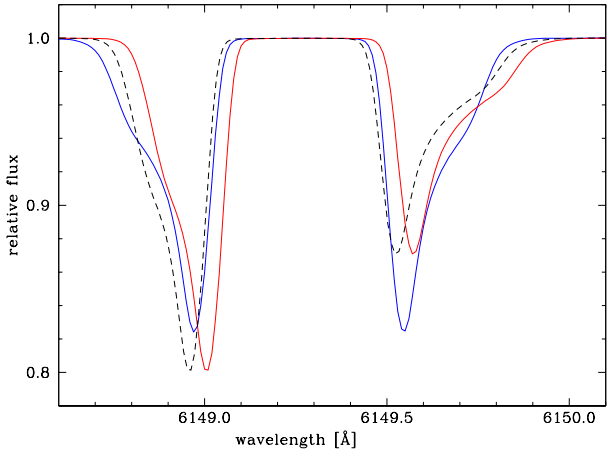
Decidedly, the behaviour of the various lines of multiplet 74 of Fe II in the incomplete Paschen-Back regime cannot easily be predicted. Line shifts, intensities and asymmetries vary with magnetic field strength, field inclination and total line opacity in the multiplet. The same holds true for the numerous other lines in the solar spectrum and in stellar spectra which show the incomplete Paschen-Back effect.

## 6.2 Ghost components

As pointed out in Condon & Shortley (1935) and in more detail in Landi Degl’Innocenti & Landolfi (2004), lines appear in the incomplete Paschen-Back regime which are normally forbidden under the selection rules for electric dipole transitions. This has to be ascribed to the fact that  $J$  is no longer a good quantum number and there occurs J-mixing of the various levels belonging to a particular term. These lines are sometimes referred to as “forbidden lines”, but we prefer here to call them “ghost components” or “ghost lines” in order to avoid confusion with the well known forbidden lines in astrophysics which arise from metastable levels.

Take multiplet 74 of Fe II as an example. Without a magnetic field we have 8 transitions at  $\lambda 6456.383$ ,  $6416.919$ ,  $6407.251$ ,  $6247.557$ ,  $6239.953$ ,  $6238.392$ ,  $6147.741$ , and  $6149.258$ , but J-mixing leads to an additional 4 transitions at  $\lambda 6408.897$ ,  $6284.959$ ,  $6192.961$ , and  $6156.642$ . At a field strength of  $4$  T, the total strength of the  $\lambda 6408.897$  “ghost line” reaches 15% of the strength of the nearby allowed  $\lambda 6407.251$  line. Generally, the “ghost lines” are extremely weak in fields of the order of  $0.1$  T but their strength can become comparable to that of many allowed components once field strengths of  $10$  T are exceeded.

This led Mathys (1990) to speculate that some ghost lines originating in strong multiplets of abundant elements could possibly become observable in selected Ap stars whose atmospheres are permeated by fields in the range of  $3$ – $5$  T in



**Figure 9.** A comparison between the mean profiles from 9 different Oblique Rotator models as detailed in the text, calculated in the partial Paschen-Back regime (red) and in the Zeeman regime (blue). The wavelength shift PB minus Zeeman is  $-0.048$  Å. The dashed profile (black) represents the PB-profile shifted by this amount, allowing a better comparison of the respective *shapes* of the profiles.

some parts. We are rather sceptical as for the observability for reasons obvious from Fig. 8: “ghost lines” can show up only in fairly strong fields so that the observable profiles will invariably be severely diluted unless the star is not only endowed with a reasonably extended strong-field region but also exhibits only weak field gradients.

## 6.3 The Fe II doublet at $6149$ Å and the magnetic field modulus

Originally, the main rationale for our investigation was to establish whether or not measurements of the magnetic field modulus  $H_s$  from the splitting of the Fe II  $\lambda 6149$  Zeeman doublet could be affected by the incomplete Paschen-Back regime and possibly lead to incorrect results when interpreted in terms of standard Zeeman splitting.

To this end we have calculated a grid of profiles for 9 Oblique Rotator models with various inclinations and eccentricities, all with a field modulus of  $H_s = 1.45$  T, but with dipole strengths ranging from  $0.86$  to  $1.40$  T (in a centred dipole model, the polar field strengths would be twice these values). Means were taken over the wavelengths of the 9 respective centres-of-gravity, blue and red component separately, both for the incomplete Paschen-Back and the Zeeman regime. PB-profiles are found to be *always* red-shifted by about  $0.05$  Å relative to the Zeeman-profiles, but there is no change in the splittings (see Table 1); the value of  $H_s = 1.442$  T in the former regime is nearly the same as  $H_s = 1.457$  T in the latter. PB-profiles can become dramatically asymmetric: a deep and relatively narrow blue component stands in sharp contrast to a shallower red component characterised by a strong and extended redward wing (Fig. 9).

These models (and all other models calculated on a random basis) have not revealed any undesirable behaviour of the doublet as far as the determination of  $H_s$  is concerned,

**Table 1.** Mean wavelength positions in the Zeeman and in the partial Paschen-Back regime of the centres-of-gravity of the blue and red components respectively of the  $\lambda 6149$  Zeeman doublet for different oblique rotator geometries but a constant field modulus of  $H_s = 1.45$  T. Wavelengths are given in Å, the scatter  $\sigma$  in mÅ.

	$\lambda_{blue}^{COG}$	$\sigma$	$\lambda_{red}^{COG}$	$\sigma$	$\Delta\lambda^{COG}$	$\sigma$
Zeeman	6148.916	0.4	6149.602	0.3	0.686	0.5
P.-B.	6148.968	0.5	6149.647	0.5	0.679	0.5

although, as discussed above, sizeable wavelength shifts are encountered. With all the necessary caution, we deem it highly probable that these findings hold true for all magnetic geometries.

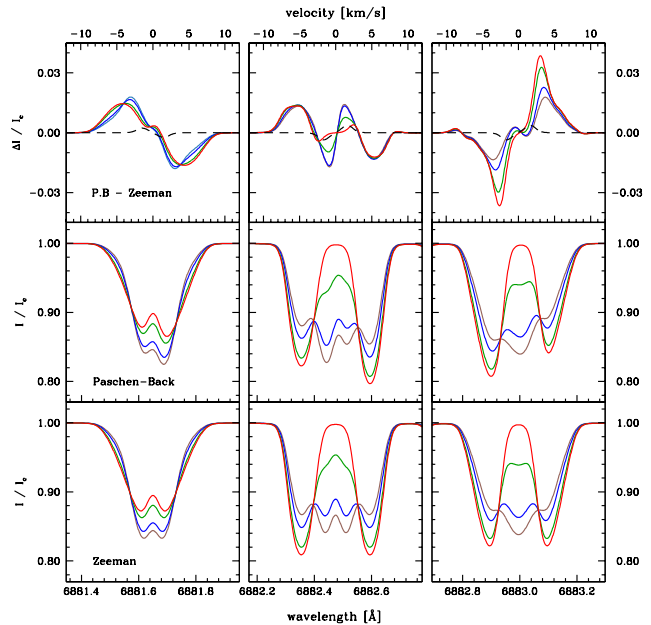
Let us note that the scatter about the mean COG wavelengths in Table 1 is extremely small; PB-profiles exhibit somewhat larger differences between each other than the Zeeman-profiles. This suggests that at least some of the lines formed in the incomplete Paschen-Back regime can provide increased diagnostic content for magnetic field mapping. Inclusion and correct treatment of these lines is expected to increase the reliability of magnetic maps.

#### 6.4 Doppler mapping

A few words of caution are appropriate for the aficionados of (magnetic) Doppler imaging. In fact, if one looks at the list of 12 Cr I lines used by Kochukhov et al. (2004) for the mapping of HR 3831, the lines at 6881.65, 6882.48, and 6883.00 Å, all belonging to multiplet 222, are definitely in the partial Paschen-Back regime, given the narrow wavelength spread of these 3 lines. The quite uncertain oblique rotator model with a centred dipole proposed by these authors – detailed analyses based on full Stokes profiles usually find non-negligible quadrupole contributions – predicts a polar field strength of 0.25 T. We calculated local intensity profiles for this field and various angles between field vector and line of sight. The respective Zeeman and PB intensity profiles differ by up to 20% as can be seen in Fig. 10.

Translated to velocity space, the use of Zeeman profiles instead of the correct PB profiles will thus result in spurious over- and under-abundances at relative velocities ranging from  $\pm 3$  km s<sup>-1</sup> to  $\pm 6$  km s<sup>-1</sup> in these 3 lines. Note that the differences between PB and Zeeman profiles hardly depend on the angle in the case of  $\lambda 6881.65$ , whereas a strong dependency is found for  $\lambda 6883.00$ . In the latter line, differences are largest for a longitudinal field but just the opposite is true for  $\lambda 6882.48$ . Looking at the sign of the differences, one finds a global blue shift of the  $\lambda 6883.00$  PB profile and a global red shift of the other 2 lines.

Given this complex behaviour, it is difficult if not impossible to predict to what degree the Cr abundance maps derived by Kochukhov et al. (2004) may have been affected by the simplifying assumption of normal Zeeman splitting for these 3 lines. Close scrutiny of their Fig. 6 reveals that whereas  $\lambda 6881.65$  and  $\lambda 6882.48$  are reasonably well reproduced by the chromium Doppler map shown in their Fig. 8, there are significant deviations from the observed profiles in the vicinity of  $\lambda 6883.00$  near phases 0.30 and 0.78 (when the magnetic equator dominates the visible hemisphere and the poles are near the limb). Given the special behaviour of  $\lambda 6883.00$ , can we attribute these differences to pure chance



**Figure 10.** Intensity profiles of the lines of multiplet 222 of Cr I in the spectral interval 6881 – 6884 Å for a 7500 K,  $\log g = 4.0$  Kurucz (1993a) model. The magnetic field strength is 0.25 T, the respective angles between the field direction and the line of sight are 0, 30, 60, and 90° (red, green, blue, brown). Note the perfect symmetry of the components in the Zeeman regime (bottom) and its deformation by the partial Paschen-Back effect (middle). The relative difference between the two profiles reaches about 20% (top). Since the theoretical line strengths and positions do not perfectly match the Kurucz line data, very small differences occur even for zero field strength (dashed black line in the top panel). For clarity we have indicated both the wavelength and the velocity scale.

or is there some responsibility of the PB effect? The question remains open and further detailed investigations are necessary to assess the true importance of this potential problem.

## 7 CONCLUSIONS

High resolution spectral observations of magnetic Ap stars make it clear that the Paschen-Back effect cannot be neglected in the interpretation and modelling of a number of spectral lines, whether it be the Li I  $\lambda 6707$  resonance line or the Fe II  $\lambda 6149$  Zeeman doublet. Because of its simple structure, the latter is particularly useful for the determination of the magnetic field modulus  $H_s$ . We have calculated in detail the splittings of the spectroscopic terms involved in these transitions and the relative intensities of the subcomponents and found, somewhat to our surprise, that some lines can enter the incomplete Paschen-Back regime already at field strengths of a bare 0.05 T as is the case for the lithium resonance lines. Looking further to other chemical elements, we have discovered that in extreme cases (Cr I is an example), up to an estimated 18% of the lines may exhibit the transition to the partial Paschen-Back regime in Ap stars with strong magnetic fields of the order of 2 T.

The development of CossamPaschen, a modified version of COSSAM – the polarised line synthesis code established by Stift (2000) – has made it possible over the last few years

to explore the effect of the partial Paschen-Back regime on Stokes spectra. CossamPaschen allows the detailed and realistic modelling of a PB multiplet, blended with lines which are treated in the Zeeman approximation. First ever detailed Stokes profiles in realistic stellar atmospheres have been presented at the CP#AP Workshop in Vienna (Stift 2007) and provide valuable insight into the sometimes spectacular changes of selected spectral lines. These calculations show that the centres-of-gravity of the Fe II  $\lambda$ 6149 line and of its sister line at  $\lambda$ 6147 are shifted in magnetic fields, either towards the red or towards the blue, depending on line strength, magnetic field strength, and field direction. A comparison between the observations plotted in Fig. 1 and the theoretical results displayed in Figs. 4 and 5 shows gratifying agreement.

Another interesting finding is the confirmation of the existence of normally forbidden “ghost components” in strong magnetic fields. The intensity of these components is a very strong function of magnetic field strength, and in Ap stars some of them may actually significantly contribute to the *local* spectra in places with very strong magnetic fields (of the order of 4 T). However, the strong dependency of intensity and position on field strength will probably lead to the *global* signature of the “ghost components” begin washed out.

An important result of our investigation is the confirmation that  $H_s$  measurements obtained from the splitting of the Fe II  $\lambda$ 6149 line and interpreted in terms of classical Zeeman splitting do not need to be corrected for the PB effect. For all practical purposes, even in the strongest fields encountered in Ap stars, the PB splitting is not different from the Zeeman splitting. As for maps derived by means of (magnetic) Doppler mapping, we cannot provide such a reassuring confirmation and there is a real danger that the inclusion of lines subject to the partial PB regime may lead to spurious results. What can be a serious nuisance may also provide improved diagnostic capabilities and so we are looking forward to improved imaging codes incorporating the full treatment of the partial Paschen-Back effect.

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